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REPORT
CD NO.

50X1-HUM

COUNTRY	USSR	DATE OF INFORMATION	1949
SUBJECT	Scientific; Technological - Metallurgy, cutting tools		
HOW PUBLISHED	Book	DATE DIST.	18 Dec 1950
WHERE PUBLISHED	Moscow	NO. OF PAGES	5
DATE PUBLISHED	1949		
LANGUAGE	Russian	SUPPLEMENT TO REPORT NO.	

THIS IS UNEVALUATED INFORMATION

SOURCE: Issledovaniya protsessa rezaniya metallov, Mashgiz (State Scientific and Technical Publishing House for Machine-Building Literature), (LC No TJ 1230 .K56), pp 97-113.

INVESTIGATING METAL-CUTTING PROCESSES: IV. COMPONENTS OF CUTTING FORCE AND WORK

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/A Digest/

The nature of cutting forces was studied by Prof S. F. Glebov in 1933 - 1937, and the following works on the subject were published by him: "Theory of the Most Efficient Cutting of Metals," Gosmashmetizdat, 1933, "The Work of Cutting and Its Components," Vestnik Metallicheskoy Promyshlennosti (Herald of the Metals Industry), No 10-11, 1936; "The Work of Cutting and Its Components," in "Symposium of Abridged Reports of the Conference on Metal Cutting," Academy of Sciences USSR, 1937.

After considering several theories and formulas for determining the cutting force, Glebov made the following conclusions:

1. The decrease of the cutting coefficient with increasing cross section of the chip is caused by nonuniform composition of the cutting work, and changes in the chip cross section have a different effect on each component of the cutting work.

2. One component of cutting work has to follow Kick's law and, therefore, this component of work must be proportional to the cross-sectional area of the chip (or to its volume).

3. The second component of cutting work does not follow Kick's law and is proportional to the perimeter of the chip, i.e., to its surface.

4. Friction work must be considered as a certain particular type of work, consisting of two elements: friction of the chip against a cutter and friction of the cutter edge against the surface of the machined part. This work is produced by the action of forces also performing other types of work, and must be proportional to the sum of the projections of all these forces or part of them on the normal to the surface of friction.

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5. The work of coiling the chip into a spiral, considered by Professor Friedreich as a specific type of work, apparently does not require any separate consideration if it is assumed that this work is proportional to the cross-sectional area and therefore is included in the work under No 2 above.

Total work of cutting A, according to Glebov, is equal to:

$$A = Ad + Ac + Af \qquad (96)$$

where Ad is the work of deformation, Ac the work of cutting the chip off, and Af the work of friction.

Assuming that a certain part of the total friction work Af, for example m.Af, is proportional to Ad and the other part, equal to (1-m) Af, is proportional to Ac, and the proportional coefficients in both cases are respectively p and g, Glebov expresses the friction work by means of the two other types of work:

$$Af = p \cdot Ad + g \cdot Ac$$

The deformation work Ad is proportional to the cut area S_o and may be presented as:

$$Ad = k_o \cdot S_o \cdot l - k_o \cdot a \cdot b \cdot l,$$

where k_o is the average specific work of deformation for 1 cu mm of the chip.

As for the work of cutting off, Glebov considers it as proportional to the surface of the chip or, rather, to the surface of cutting. At l = const, it will be proportional to the perimeter of cutting, i.e., to the total length of the working part of the cutter.

Therefore: $A_c = k'_o \cdot L \cdot l,$ (97)

where: k'_o is the work of cutting off the chip without internal deformation related to 1 sq mm of the surface, L is the perimeter of cutting.

Then, the work of friction may be expressed as $Af = p \cdot k_o \cdot a \cdot b \cdot l + g \cdot k'_o \cdot L \cdot l$; hence, $A = (p+1) \cdot k_o \cdot a \cdot b \cdot l + (g+1) \cdot k'_o \cdot L \cdot l.$ (98)

Denoting $(p+1) \cdot k_o$ as k_1 and $(g+1) \cdot k'_o$ as k_2, we obtain finally:

$$A - k_1 \cdot a \cdot b \cdot l + k_2 \cdot L \cdot l \qquad (99)$$

After dividing A by the length of the tool path l, we will obtain the expression for the tangent force Pz:

$$Pz = k_1 \cdot a \cdot b + k_2 L \qquad (100)$$

If the chip section has the form of a parallelogram, the arc of cutting-off θ is a semiperimeter of the chip section. For such sections of the chip both perimeter and arc of cutting off are proportional to the square root of the section area S_o, i.e.,

$$\theta = r \cdot \sqrt{S_o} = r \cdot S_o^{0.5},$$

where r is the coefficient of proportionality.

Replacing θ by $r \cdot S_o^{0.5}$ and assuming $k'_2 = k \cdot r$, we obtain:

$$Pz = k_1 \cdot S_o + k'_2 \cdot S_o^{0.5} \qquad (101)$$

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Empirical formulas of the "second approximation," according to Glebov, give for the cutting force the following expression:

$$Pz = B \cdot S_o^{z} \qquad (102)$$

The exponent of S_o will be nearer to 1 with increase of the specific part of deformation work in the total work of cutting, and it will approach 0.5 when the cutting-off work attains a greater specific weight in the total work of cutting.

Glebov uses equations (101) and (102) for calculating the ratio between quantities of deformation work and cutting-off work (together with related parts of friction work) in the total work of cutting by comparing their portions: $k_1 S_o + k'_2 \cdot S_o^{0.5} = B \cdot S_o^{z}$.

Dividing both parts of the latter equation by $k'_2 \cdot S_o^{0.5}$, we obtain:

$$\frac{K_1}{K'_2} \cdot S_o^{0.5} = \frac{B}{K'_2} \cdot S_o^{z-0.5} - 1 \qquad (103)$$

The ratio of deformation work to cutting-off work is equal to the ratio of both components in formula (101) to each other, i.e., $i = \frac{K'}{K'_2} \cdot S_o^{0.5}$, and with consideration of (103):

$$i = \frac{B}{K'_2} \cdot S_o^{z-0.5} - 1 \qquad (104)$$

The works of cutting off and deformation may be expressed in the following manner:

$$Ac = \frac{1}{i+1} \cdot A; \quad Ad = \frac{i}{i+1} \cdot A \qquad (105)$$

Replacing B, k'_2 and Z by the values obtained for them experimentally, Glebov calculated that: $Ac = \frac{1}{1.52 S_o^{0.43}} \cdot A$ for gray cast iron with BHN 120, $Ac = \frac{1}{3.7 \cdot S_o^{0.45}} \cdot A$ for steel with BHN 160.

For $S_o = 1$ sq mm this gives:

when machining cast iron, $i = 0.52$, $Ad = 0.34A$, and $Ac = 0.66A$, i.e., the work of deformation is equal to half the cutting-off work or one third the total work of cutting; when machining steel, $i = 2.7$, $Ad = 0.73A$, and $Ac = 0.27A$, i.e., the work of deformation in this case is 2.7 times greater than the work of cutting off and amounts to up to three fourths of the total cutting work.

For $S_o = 8$ sq mm:

when processing cast iron, $i = 1.04$, $Ad = 0.61A$, and $Ac = 0.39A$, i.e., the deformation work exceeds the cutting-off work and comprises almost two thirds of the total cutting work. In steel machining $i = 8.06$, $Ad = 0.89A$, and $Ac = 0.11A$, i.e., the deformation work in this case is eight times greater than the cutting-off work and amounts to up to 90% of the total work of cutting.

It was assumed in all calculations that the work of friction is distributed between the two other works. Separating the friction work and considering it for both metals as equal to 10-15%, Glebov obtained the following final distribution of work in percentages of the total cutting work:

	Cast Iron	Steel
Work of deformation	40-65	65-85
Work of cutting off	25-45	5-25
Work of friction	10-15	10-15

The greatest value of cutting off corresponds to smallest sections of chips and vice versa.

S. F. Glebov was the first investigator who attempted quantitative evaluation of the role of components in the total work of cutting.

A somewhat different opinion was expressed by Rozenberg (A. M. Rozenberg, Dynamics of Milling, published by "Sovetskaya Nauka," 1945).

Rozenberg does not accept Glebov's assumption that the work of plastic deformation of chips follows Kick's law.

The law of proportional resistances established by Kick requires a series of conditions: homogeneity of physical, chemical, and mechanical properties of the materials under investigation, geometrical similarity of their shapes, geometrical similarity of their deformations, and similar rates of deformation. With the presence of all these conditions, Kick's law establishes the proportionality of forces and works of cutting respectively to squares and cubes of the linear dimensions of the body.

The process of chip forming, in Rozenberg's opinion, does not maintain the most important of the above-mentioned conditions -- geometrical similarity of deformations.

Rozenberg also disagrees with Glebov's results concerning gray cast iron: he does not believe that 40-65% of the total cutting work may be referred to deformation work in the case of cast iron.

According to Rozenberg, the necessary condition for work of deformation is a more or less considerable shifting of metal particles without breaking the strong bond among them, a factor which may hardly be expected to a great extent in the case of cast iron. Rozenberg assumes that the deformation work, if it exists at all, in machining such brittle metals as cast iron is very insignificant. The main part of the work consists of friction work. Moreover, not only friction between the cutter and chip and friction between the cutter and surface of cutting must be considered, but also the friction among metal particles being separated from each other.

In this reasoning the opposite extreme takes place. The chip-forming process in machining cast iron (if a tool has front angles which are not very large) represents, as also in steel machining, successive shifts of portions of the layer being taken off in the direction determined by the angle B_1. Kuznetsov considers the work of cutting as follows (V. D. Kuznetsov, Physics of Solids, Vol III, published by "Krasnoye Znamya," Tomsk, 1944):

For the length l the work of cutting is determined by the formula:

$$A = Pz \cdot l$$

The work of cutting may be divided into two parts: $A = A_1 + A_2$.

The first part A_1 is used for plastic compression of the object being machined. It is proportional to the volume of the removed layer:
$A_1 = k_1 \cdot a \cdot b \cdot l = k_1 \cdot S_o \cdot l$.

The second part of work A_2 is used for friction of the front and rear edges of the cutter against the chip and machined surface. It is proportional to the surface of contact and is expressed by the equation: $A_2 = k_2 \cdot b \cdot l$.

Hence, $$A = Pz \cdot l = k_1 \cdot a \cdot b \cdot l + k_2 \cdot b \cdot l,$$

from which $$Pz = k_1 \cdot a \cdot b + k_2 \cdot b.$$

Investigations, which yielded a series of essential experimental data on the physical nature of components of cutting forces and work, were conducted by Savitskiy in V. D. Kuznetsov's laboratory. He studied the effect of preliminary heating in the range 16-400° on the cutting process in copper and also the effect on the same process of cold working in the range 0-58.4%.

The process of free cutting was realized on a planing machine with a speed of 0.48 m/min and cutting angle $\delta = 55°$. Cutting forces were measured with a specially constructed dynamometer. Chips were measured, and particular attention was paid to correct determination of the cross section of a chip. The relative and absolute contraction of a chip was calculated from values of the cut area S_o and the chip cross section S. Further, investigators computed cutting stress σ_{ν}, effective stress σ_e, coefficients k_1 and k_2, and exponent ξ in formula (68) for cutting force.

Simultaneously, the mechanical characteristics of copper at various temperatures were measured: Brinell hardness, actual breaking strength, arbitrary yield point, and tensile strength.

Analysis of data obtained in these experiments was conducted by V. D. Kuznetsov and described in his work Physics of Solids, Volume III.

It may be concluded that experiments by Savitskiy give good confirmation to the theory of the cutting process as a process of successive shears.

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